Source Mechanisms of Recent Moderate Earthquakes Occurred in Honaz-Denizli (W Turkey) Graben Obtained by Regional Broadband Waveform Inversion

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The Western Anatolia Horst-Graben System is one of the most seismically active regions in Turkey. Denizli Graben System is located in an area where three major E-W grabens join at their eastern ends. In this study, we have analyzed focal mechanisms of 10 earthquakes by using P wave's first motion polarities with FOCMEC algorithm and regional Body-Waveform inversion method developed by Dreger (2003). The analyzed events occurred in different parts of the Denizli Graben and they show near horizontal T axes directions oriented almost NE-SW (average value of 220°). T axes indicate that the Denizli Graben opens at the direction of NE-SW. However, the earthquake source parameters exhibit normal faulting mechanism with strike slip components (oblique faults). All focal mechanisms have large dip angle values, except one earthquake. The centroid depths are lying in the range of 6-8 km. The results are consistent with the tectonic setting which is formed by the movement of African and Eurasian plates.

As a consequence of the continental collision of the Eurasian and African plates, the Anatolian plate, which is bounded by the right-lateral strike slip North Anatolian Fault and the left lateral strike slip East Anatolian Fault, has been moving in westward direction and simultaneously rotating counterclockwise since ~5 Mya. The African Plate was subducting northwards under the southern side of the Anatolian Plate along the Aegean-Cyprean subduction zone. The N-S extensional regime has been formed mainly by the movement of the Anatolian Plate. Furthermore, the subduction of the African Plate under the southern margin of the Anatolian Plate was the cause of the formation of E-W, NW-SE, NE and NW trending normal faults resulting the grabens in the Western Anatolia (among others, Dewey and Şengör, 1979; Eyidoğan and Jackson, 1985; Taymaz et al., 1991; Taymaz and Price, 1992; Koçyiğit et al., 1999; Gürer et al., 2003). The West Anatolian Horst-Graben System as mentioned above. The West Anatolian Horst-Graben System is characterized principally by E-W trending major horsts and grabens such as (from north to south) Bakırçay, Gediz, Külüük Menderes, Büyük Menderes and Gököva grabens. There are NW-SE and NE-SW oriented comparatively short and local grabens located within the major E-W trending horsts. The tectonic origin and structural developments are summarised by Bozkurt (2001 and 2003), Koçyiğit (2005) in detail. Denizli Graben System which is located in an area where three major E-W grabens join at their eastern ends (Figure 1) forms the eastern continuation of the Büyük Menderes Graben. It is separated from the Gediz Graben by a topographic high around Buldan and from Külüük Menderes Graben. The Denizli Graben is bordered by the Çökelezedağ Horsts in the north, Babadağ and the Honazdağ Horsts in the south, respectively. It is traversed by one of the faults of the Laodikia Fault Zone which also controls the northern margin of Acipayam Graben in the central part. The Denizli Graben System is a NW-SE trending basin about 50 km in length and 25 km in width. It comprises two Quaternary sub-basins, namely the Çürekusu Graben in the north and the Laodikia Graben in the south (Kaymakçı, 2006).
Figure 3: Simplified tectonic map of the Denizli Graben and its vicinity. LG: Ladılık Graben, PZ: Pamukkale Fault Zone. White epicenters show earthquakes that have been analysed in this study. Black epicenters belong to earthquakes with magnitude M>3.5 taken from ISC catalogs during the period of 2004-2008. Black beachballs are moment tensor solutions while gray beachballs are first motion solutions. The numbers above the beachballs indicate event time or date, and fault data is taken after Şaroglu et al. (1992).
Development of the Denizli Basin is started at 14 Mya years ago (Westaway, 1994) and total slip is reported as 1050 and 2080 m according to Koçyiğit (2005). The average slip rate is calculated as 0.14-0.15 mm/year by Koçyiğit (2005). The Denizli Graben System consists of 4 segments: Buldan-Pamukkale, Honaz, Kocabaş and Kakklik Segments (Koçyiğit, 2005). The pattern of shallow seismicity is diffused over a band along the major graben systems and characterized by moderate earthquakes in the western Anatolia horst-graben systems.

Even though, the instrumental period is characterized by small to moderate seismic activities including large and destructive earthquakes occurred in historical times in Denizli Graben System. However, there are few studies about focal mechanism parameters of earthquakes occurred in this area. The recent installation of broadband stations since 2004 by Kandilli Observatory and Earthquake Research Institute (KOERI) make it possible to recover of small to moderate earthquakes that occur at local and regional distances using regional body-waveform analysis. In this study, we present a regional study of the moderate size seismicity (M≥3.9) in the Denizli Basin, from 2004 to 2008. Both local and regionally recorded seismic waves (for seven earthquakes) and first motion polarities (for three earthquakes) were used to get a better understanding of the earthquake source, in particular, seismic:moment, focal mechanism and centroid depth. We also used the orientation of the P and T axes, obtained from the moment tensor analysis in order to improve the understanding of regional tectonics and kinematics.

A time-domain inverse procedure (e.g., Dreger and Romanowicz, 1994; Pasyanos et al., 1996) was used to estimate the seismic moment tensor of events shown in Figure 1. This procedure is designed to obtain reliable solutions using the least number of stations. Three component waveform data recorded only at one station would be sufficient, but few stations with good azimuthal coverage generally give more reliable results. However, typically only two or more three-component broadband stations are required to obtain a unique solution (Dreger and Helmberger, 1993). In this procedure, the general representation of seismic sources is simplified by considering both a spatial and temporal point-source.

\[ U_n(x,t) = M_l \cdot G_{nl}(x,z,t) \]  

\( U_n \) is the observed nth component of displacement, \( G_{nl} \) is the nth component of Green’s function for specific force-couple orientations, and \( M_l \) is the scalar seismic moment tensor, which describes the strength of the force-couples. The general force-couples for a deviatoric moment tensor may be represented by three fundamental-faults, namely a vertical strike-slip, a vertical dip-slip, and a 45° dip-slip. The indices i and j refer to geographical directions. The equation (1) is solved using the linear least squares method for a given source depth. In this distribution only the deviatoric seismic moment tensor is solved for, and the inversion yields the Mi which is decomposed into the scalar seismic moment, a double-couple moment tensor and a compensated linear vector dipole moment tensor. The decomposition is represented as percent double-couple (Pdc) and percent CLVD (PCLVD). Percent isotropic (PISO) is always zero for deviatoric application. The double-couple is further represented in terms of the strike, rake and dip angles of two nodal planes. The basic methodology and decomposition of the seismic moment tensor is described by Jost and Herrmann (1989).

Earthquake source depth is found iteratively by finding the solution that yields the largest variance reduction. The results of the moment tensor inversion are generally not very sensitive to location errors. Dreger and Helmberger (1993) and also Pasyanos et al. (1996) have shown that errors of up to 15 km in epicenter location are less important at a distance range between 50 km to 400 km. It is assumed that the event location is well represented by the high frequency hypocentral location, and a low frequency
Figure 2: Velocity depth model of Deniliquin (modified from Akyol et al., 2006).

The velocity model was determined by a trial and error method that gave the best fit between observed and calculated seismic responses. The model was then iterated until a final model with a high correlation coefficient was achieved. The final model was then used to calculate the depth function.

The depth function was calculated following the method of Akyol et al. (2006). The depth function was then compared with the observed seismic response.

The depth function was calculated using the following equation:

\[ \text{Depth} = \frac{1}{2} \left( \frac{\text{Velocity}_1 + \text{Velocity}_2}{2} \right) \]

where \( \text{Velocity}_1 \) and \( \text{Velocity}_2 \) are the velocities at the two observed seismic stations.

The depth function was then used to calculate the depth of the velocity function.

The resulting model shows how the velocity model compares with the observed seismic response. The model is depicted in a velocity-depth graph with a solid line indicating the observed response and a dashed line indicating the calculated response.

The model was then compared with the observed seismic response, and the depth function was adjusted accordingly.

Second, the simplified representation above assumes that the source function is uninformative of all moment tensors. This assumption may be violated in actual cases, and the source function may contain additional information.
Figure 1 shows all of analyzed earthquakes at the current study. Three of the events (12 October 2006, 25 April 2008, and 24 December 2008) occurred at the eastern end of the Denizli Graben and other three events (5 June 2006 cluster and 10 January 2008) occurred at the western end where Denizli Graben intersects with the Büyük Menderes Graben, one of them (23 January 2007) occurred NW end where Denizli Graben assemble with Gediz Graben. The focal mechanisms reflect that the extensional regime is dominant with the direction of NE-SW in the Denizli Graben. There are two other events occurred at adjacent grabens (14 May 2004 and 29 January 2005) exhibiting normal faulting mechanisms. Figure 3 shows an example of the inversion result for 25 April 2008 that is the largest event (Mw 4.8) of the all analyzed earthquakes. However, data from only 3 stations at available 10 in the distance range between 90 and 300 km, could be used. The observed and calculated seismograms were band-pass filtered at 0.02-0.05 Hz. The Signal-Noise ratio is generally good at frequencies above 0.02 Hz for events of this moderate size (Dreger and Helmberger, 1993). The variance reduction (VR) is %70, and the misfit between observed and calculated seismograms is good enough. Source depth (8 km) is slightly smaller than Global CMT Project (GCMT) (12.2 km) and INGV solutions (14 km). We obtained Mw=4.7, which is smaller but comparable with GCMT (Mw=5.0) and INGV solutions (Mw=4.9). The focal mechanism indicates normal faulting with strike-slip component in a good agreement with regional tectonics.

The azimuthal distribution of stations is important for the inversion procedure. We used 3 stations located at different azimuths (Figure 3). The azimuthal gap is increased with earthquake magnitude and also with S/N ratio. Dufumier and Rivera (1997) have pointed out that an azimuthal coverage below 60° ensures a stable solution. In this case, the problem is that our results how usable to make tectonic interpretation? Even though the first motion polarity results give initial movement of the rupture process, we could not expect important changing the mechanism during the rupture. Because our events have 2-3 sec source time due to their magnitudes and most probably their fault mechanisms have not changed during whole rupture process. So, it means that first motion polarity results could control consistency of the moment tensor inversion results obtained by this study. However, for some cases, TOA angles calculated by HYPO71 could be same for most stations even they have different distances. P- and T- axes from earthquake focal mechanism are one of the most commonly used tectonic stress indicators. The average direction of T- axes is 220° that means the NE-SW extensional regime is responsible for generation of the Denizli Graben. On the other hand, the average direction of P- axes is obtained to be 29°. In this study, we have studied source parameters of 10 earthquakes by using regional waveform analysis and P- wave first motion polarities. The earthquakes have been separated to two clusters: East and West clusters. Focal mechanisms are similar to each other within those clusters and dominated by normal faulting mechanisms with strike-slip components. All focal mechanisms have large dip angle values, except one earthquake. The centroid depths are in the range of 6-8 km. The earthquakes have near horizontal T-axes oriented almost NE-SW. T- axes indicate that the Denizli Graben opens in the direction of NE-SW. This is also consistent with tectonic settings formed by the movement of African and Eurasian plates. Mw which is derived directly from Mw is considered to be the most reliable magnitude type. Therefore, one of the aims of this study is to calculate more accurate magnitudes in the Denizli Graben. Even though the focal mechanisms are consistent with tectonic setting, we found smaller Mw value compare with Mw. The differences or discrepancy between magnitudes are not significant and probably they are caused by wave propagation effects which result error in Mw or lack of energy at frequencies 0.02 Hz which result error in Mw. The low frequency energy may not be propagating through the crust, thus the coming wave carried less energy and it affects the seismic moment. On the other hand, reason of the discrepancy may be involved frequency dependent Q, stress drop and high crustal rigidity.


Figure 3: Summary of solutions obtained for earthquakes of 25 April 2008 (p, q, r, s, t). (p) Waveform fits of calculated (dashed) to observed (solid) seismograms. Above each trace station code, the p–wave first motion polarities (up) are shown. (q) Moment tensor inversion results. (r) (s) Possible solutions. (t) (u) (v)


